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Evaluation of the thermal environment for condensation and mold problem diagnosis around built-in furniture in Korean apartment buildings during summer and winter

Hyun-Hwa Lee[a], Hae-Rin Oh[a], Jae-Han Lim[a], Seung-Yeong Song[a,*]

[a]*School of Architecture, Ewha Womans University, Seoul 03760, Republic of Korea*

Abstract

Recently, condensation and mold problems in apartment buildings have been on the rise due to increased insulation and airtightness performance for energy savings. Occupants in residential buildings have suffered property damages due to condensation and mold on built-in furniture, especially in Korean apartment buildings. Generally, condensation and mold growth on built-in furniture were found during summer and winter on the back panels of the furniture and adjacent surfaces of the walls, floor, and ceiling. These problems are related to the weather and indoor room conditions. To solve these problems, it is necessary to investigate the thermal environment around the built-in furniture and in living spaces during summer and winter. The aim of the study was to analyze the thermal environment around the built-in furniture during summer and winter. Through field measurements at apartment buildings that were constructed from 1990 to 2014, the thermal conditions around the built-in furniture were assessed. Results indicate that nine target apartment buildings did not incur condensation during summer, but they suffered from mold. Four apartment buildings, which were constructed after 2004, incurred condensation during winter, but they did not suffer from mold. Based on our results, we have prepared a solution design guide for preventing condensation and mold around built-in furniture.

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Keywords: Thermal environment; Korean apartment buildings; Condensation and mold risk

1. Introduction

In recent years, the performance requirements of insulation and airtightness have been raised considerably for energy savings in Korean multifamily buildings [5,6]. As these buildings now have advanced energy performance

* Corresponding author. Tel.: +82-2-3277-3591; fax: +82-2-3277-4442.
E-mail address: archssy@ewha.ac.kr

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from increased insulation and airtightness, the possibility of condensation and mold growth in the building's interior is on the rise due to the generation of interior water vapor or the inflow of humid air from the outside in certain cases. In the past, multifamily buildings had poor insulation and airtightness performance, and the damage from condensation and mold was insignificant. However, damages caused by condensation and mold account for 16% of disputes in Korean multifamily buildings in recent years. The causes of these conflict cases concerning condensation and mold are diverse and include thermal bridges and an absence of insulating material. In particular, condensation and mold growth in the wall or area of the ceiling adjacent to the back panels of build-in furniture is causing physical damage to properties. In the built-in closets of Korean multifamily buildings, condensation and mold usually develop on the back panels and on the walls, floor, and ceiling adjacent to the furniture. The scale of damages is especially hard to measure, as it is difficult for the occupants to properly maintain these spaces during their residence. The Korean climate is very hot and humid during the summer, which increases the probability of mold growth on the built-in furniture, as the humid air comes in from the outside. In the case of winter, condensation and mold growth in built-in furniture can occur depending on the outside environment and the living conditions of occupants inside the apartment.

Fig. 1 (a) (b) (c) Condensation and mold problems around the built-in furniture; (d) schematic of cross-section of built-in furniture

Various studies have been performed previously to analyze and attempt to solve the problem of condensation and mold growth in Korean multifamily buildings. Minimizing the thermal bridge in walls, windows, and doors and improving insulation performance, ventilation, and dehumidification have been discussed as solutions. For major studies conducted in Korea, literature is available on solutions for condensation development focusing on materials for finishing and door and window framing, such as "A Study on the Method for Determining the Extent of Insulation to Prevent the Inside Surface Condensation at Thermal Bridges [11]," and on thermal performance evaluation methods, such as "Analysis of evaluation methods for the condensation resistance with window types at design stage [13]" and "Condensation Risk Evaluation Using Surface Temperature Analysis of the Glazing System [12]." Recently, design standards for temperature and humidity against condensation were suggested through an indoor temperature and humidity survey in multifamily buildings to set standards at a national level for determining condensation in such housing [6,7]. Currently, various studies are in progress on condensation incidence in spaces, such as bedrooms and dressing rooms, where furniture pieces, such as built-in closets, are installed. Additionally, studies on the installation arrangement and materials for built-in furniture [9,10], including "Evaluation on the Thermal Environment inside the Built-in Furniture in New Apartment Buildings in Winter [1]" and "Evaluation on the Thermal Environment inside the Built-in Furniture in Apartment Buildings in Summer [2]," were performed. In "An Evaluation of Mold Growth Risks in Trouble Spots in an Apartment Building using Computer Simulation [3]" conducted on a building with mold problems, it was found that spots of condensation incidence may not necessarily match those of mold incidence. Reducing the indoor humidity through ventilation or using materials with antimicrobial properties, rather than reducing the thermal bridge in the dressing room of multifamily buildings, were suggested as solutions. "The Status and Cause of Mold Infestation in Apartment Houses Based on a Case Study [8]," also found that spots of frequent condensation incidence in multifamily buildings may not exactly match those of mold incidence. In addition, the annual mold incidence risk was analyzed through a simulation of mold incidence risk in potential problem areas in multifamily buildings [8]. Currently, there is no set regulation available for the prevention of mold in Korea. It has easily been confirmed from previous studies that the mold incidence risk is considerable in summer time, however. Vereecken and Roels [21] revealed moisture in the calcium silicate board was found to result in a decrease in thermal resistance and moisture could be redistributed inward resulting in a higher surface and indoor relative humidity. Ojanen [22] presented the numerical study to evaluate the moisture buffering effect of log house wall structure and the possibilities of hygroscopic log structure to improve the indoor conditions under cold, northern climate conditions. A study was performed to predict the relative humidity and temperature ranges in the space between the built-in furniture and the wall through microclimatic computational fluid dynamics (CFD) modeling of the moisture movement [19]. It seems that condensation and mold are caused by the lack of air behind the furniture due to the cold surface temperature and high amount of water vapor. Using particle image velocimetry (PIV), it was confirmed that the discharge behind the furniture increased as the air space increased between the furniture and the wall [18].

Therefore, research on the development of condensation and mold growth in built-in furniture or dressing rooms is necessary to produce solutions to the condensation and mold problem in multifamily buildings. In particular, it is necessary to understand how the characteristics of the indoor thermal environment change when residents occupy the apartments to analyze the condensation and mold occurrence in the areas of existing multifamily buildings where built-in furniture is installed. However, in previous studies, little research was done on the characteristics of the area of furniture installation and the possibility of condensation and incidence inside the built-in furniture when occupants were residing in the apartments. In this study, therefore, the thermal environment around the built-in furniture was assessed to study the phenomenon of condensation and mold growth in the furniture installed in multifamily buildings. Practical cases of condensation and mold damage to built-in furniture studied to confirm the typical problem areas in built-in furniture. Finally, this study aimed to provide a database regarding the conditions for condensation and mold incidence by analyzing the characteristics of the thermal environment of multifamily buildings during summer and winter when occupants were residing in the apartments and to suggest thermal environmental standards for prevention of condensation and mold growth inside built-in furniture.

2. Plans for field tests

2.1. Measurement method

This study investigated the thermal environment of the space surrounding built-in furniture to confirm vulnerable areas for condensation and mold. Measurements were performed on the space where the furniture was installed to set a level for the prevention of condensation and mold growth inside built-in furniture.

To obtain baseline data on the trouble spots for condensation and mold inside built-in furniture, 12 apartment apartments from multifamily buildings located in Seoul and the Gyeonggi Province were measured during summer and winter. During the measuring period, thermo-hygro sensors were installed in the balcony, living room, bedroom, and interior of the furniture of all subject apartments, and the measurements were performed at 10 minute intervals. (Table 1 for reference)

Table 1. Description of measurement method.

Classification	Specification
Measurement Equipment	Temperature and humidity automatic recorder (TR-74Ui)
Measurement Point	Living room, Built-in Furniture, Bedroom, Balcony
Performance measurement method	10 minute intervals, 168 hours of continuous measurement
Measuring period	14.Jan.2015–18.Jan.2015
	9. July. 2015– 30.August.2015
	21.Dec.2015–21.Feb.2016

2.2. Description of field test apartments

A variety of apartments was selected, which were built between 1990 and 2014. The information on the living patterns of occupants was obtained via interview with the occupants of each subject apartment.

The number of occupants in the apartments varied from 2 to 4. The area of the 12 apartments ranged between 59 m^2–134 m^2. Table 2 shows the maximum U-values of the walls, roof, floors, and windows of each apartment based on the surface thermal transmittance provided in regulations.

As is shown in Table 3, the subject housings can be classified into four different types with built-in furniture through plan analysis. Section A is a type of housing with built-in furniture installed adjacent to external wall and is considered to have the highest possibility of condensation and mold incidence due to the decrease of temperature around the back panels of the furniture. Section B is a type of housing that has the back panels of the built-in furniture adjacent to a space heated inside the apartment and is thought to have low probability of condensation and mold inside the furniture. Section C is a type of housing in which the back panels of the built-in furniture adjacent to the bathroom wall, and it is thought that the hot and humid air coming from the bathroom would possibly flow to the back panels of the furniture. Section D is a housing arrangement in which the balcony, core, and the wall facing the back panels of the furniture meet each other, and this type is exposed to the surrounding environment during summer and winter. Thus, it is a section type that is also vulnerable to condensation and mold like Section A.

Characteristics of each subject apartment were discussed through interviews with the occupants. Apartments A, D, G, and K had damages caused by condensation during winter. Apartment A had condensation in the built-in furniture and windows. Apartment D had condensation in a corner of the bedroom. In Apartment G, the condensation occurred around the windows of the living room. Lastly, in Apartment K, the condensation was observed in the windows and the areas of wall adjacent outside and the corner of the ceiling in the living room. All apartments operated the radiant floor heating except for Apartment I, which did not heat the room where the built-in furniture was installed. The nine apartments measured operated air conditioners and dehumidifiers intermittently during summer. All apartments were installed ventilation systems, but occupants did not use ventilation systems.

Apartment L is located on the ground floor and the doors of the built-in furniture were a gallery door type. The rest of the apartments were located on typical floors and the doors of the built-in furniture were a general door type (Fig. 2).

Table 2. Summary of target apartments.

Apartment	Measuring Period		Year of Completion	Allowed Maximum U-value (W/m^2K)				Persons	Area (m^2)	Orientation
	Summer	Winter		Wall	Roof	Floor	Window			
A	X	O	Jun 2006	0.47	0.29	0.35	3.84	4	84	SE
B	X	O	Jun 2006	0.47	0.29	0.35	3.84	4	84	SE
C	O	O	Jan 1990	0.58	0.41	0.58	3.37	3	112	S
D	O	O	Jun 2004	0.47	0.29	0.35	3.84	3	85	S
E	O	O	Dec 1995	0.58	0.41	0.58	3.37	2	69	SW
F	O	O	Apr 1999	0.58	0.41	0.58	3.37	2	59	E
G	O	O	Jan 2011	0.47	0.29	0.35	3.84	3	84	S
H	O	O	Aug 2010	0.47	0.29	0.35	3.84	4	134	S
I	O	O	Dec 2000	0.58	0.41	0.58	3.37	3	115	S
J	O	O	Dec 2004	0.47	0.29	0.35	3.84	2	114	SW
K	X	O	Jan 2014	0.36	0.20	0.30	2.10	2	84	S
L	O	O	Dec 1998	0.58	0.41	0.58	3.37	4	84	E

Table 3. Section types around built-in furniture.

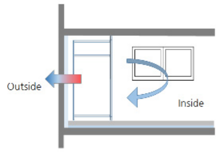
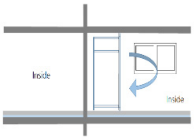
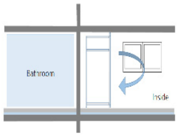
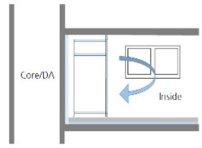
Classification	Section A	Section B	Section C	Section D
				
Measured Apartments	A,G,H,K	D,G,I,J	E,F,L	C

Fig. 2. a) General door type of built-in furniture (except Apartment L); b) gallery door type of built-in furniture (Apartment L).

3. Results of field tests

3.1. Characteristics of weather conditions

Fig. 3 shows the climate data for Seoul. The Korean summer spans between June and August and the winter between December and February and cooling and heating, respectively, are necessary during these seasons. During summer, the mean temperature is 23.9 °C, the minimum temperature is 13.7 °C, and the maximum temperature is 34.1 °C. For relative humidity, the mean is 79.3%, the minimum is 42%, and the maximum is 100%. In winter, the mean, minimum, and maximum temperatures are -1.7 °C, -16.5 °C, and 13.7 °C, respectively, and the relative humidity mean, minimum, and maximum are 66.1%, 23%, and 100%, respectively.

Due to these characteristics, the possibility of condensation is high during the winter due to the temperature difference between the interior and the exterior, and mold can grow around the trouble areas that are vulnerable to condensation due to the increase of relative humidity. During the summer, the hot and humid exterior air flows into the interior, and the condensation and mold may occur due to the increase of the interior's absolute humidity.

The occupants sporadically heated the apartment, usually by radiant floor heating during winter, and they sporadically cooled the air with a dehumidifier and an air conditioner during summer.

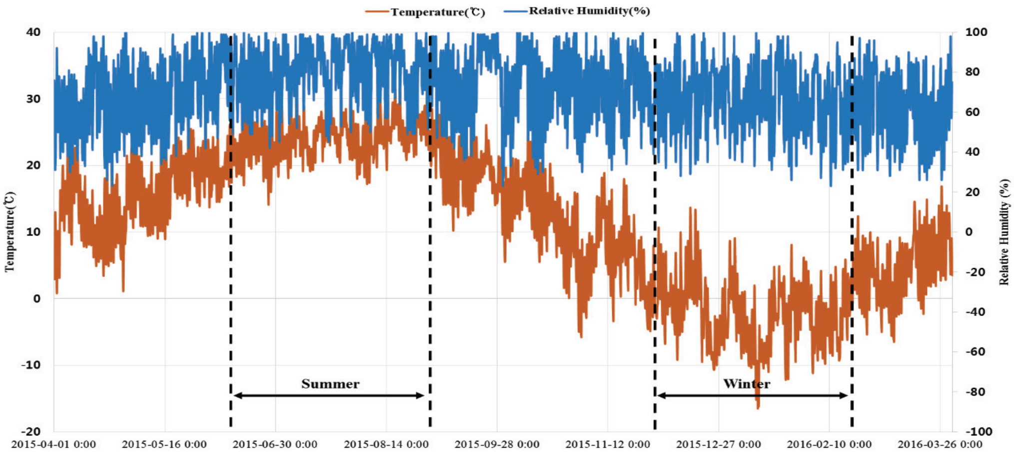


Fig. 3. Weather conditions in Korea.

Table 4. Thermal characteristic of measured apartments

		Winter				Summer			
		Balcony	Living Room	Room	Built-in Furniture	Balcony	Living Room	Room	Built-in Furniture
Temperature (℃)	Maximum	37.2	27.6	26.5	25.4	39.0	31.9	31.1	30.8
	Average	9.7	21.9	21.2	19.8	28.2	28.1	28.0	28.1
	Minimum	-1.3	5.0	6.4	4.8	21.1	22.0	23.9	23.4
Relative Humidity (%)	Maximum	100.0	74.3	73.2	74.0	100.0	93.0	86.3	83.2
	Average	49.1	39.2	40.0	42.3	24.0	67.6	67.4	65.0
	Minimum	6.0	11.0	13.8	16.0	71.0	35.0	39.0	36.0

3.2. Winter

The temperature and relative humidity of the twelve target apartments were measured in the winter. In the interior of the built-in furniture, the temperature was a maximum of 25.4 °C and a minimum of 4.8 °C with a mean of 19.8 °C. The humidity was a maximum of 74.0% and a minimum of 16.0% with a mean of 42.3%. (Table 4)

The distribution of the interior temperature of the built-in furniture ranged between 15 °C and 25 °C and that of the living room and the room with the built-in furniture was distributed between 20 °C and 25 °C. It was confirmed that the interior temperature of the built-in furniture was not directly influenced by the temperature set in the living room and the room with the built-in furniture. In the case of the interior absolute humidity of the built-in furniture, as it is a value that demonstrates the amount of water vapor in the occupying space, and the influence of the humidity on the interior thermal environment of the built-in furniture was studied. The influence of the interior absolute humidity of the built-in furniture was found to have a direct relationship with the quantity of water vapor in the living room and the room with the built-in furniture (Fig. 4).

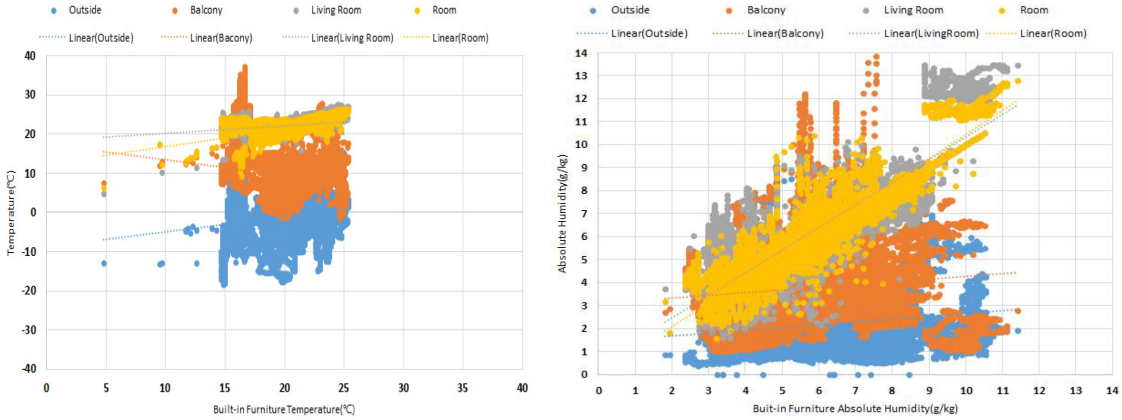


Fig. 4. (a) Correlation between built-in furniture temperature and outside, balcony, living room, and room temperature in winter; (b) correlation between built-in furniture absolute humidity and outside, balcony, living room, and room absolute humidity in winter.

Fig. 5(a) shows the interior dry bulb temperature (DBT) of the built-in furniture of each apartment. Fig. 5(a) is a graph of cumulative frequency values of all measured apartments, and if the total line is located on the right side, it means that the interior temperature of the built-in furniture is high. The apartments with the lowest interior temperature of their built-in furniture were C, I, H, and G. In the case of Apartment C, the fact that the space adjacent to the built-in furniture is a core space may be the reason for the low temperature of core space. In Apartment I, it is thought that the interior temperature of the built-in furniture is low because the furniture is installed adjacent to the external wall. Apartment H had the furniture installed adjacent to the external wall of the built-in furniture, thereby having a low temperature of the built-in furniture. Apartment G had the furniture installed adjacent to the entrance space. This area is usually not heated in comparison to other heated spaces, and this probably maintains the low temperature inside the furniture. The built-in furniture in Apartment J was maintained at the highest temperature. The closet of this apartment is located in an area where it does not meet the corners of the wall and core space, so it is highly influenced by the thermal environment of the interior space. Thus, it is thought to be effective in preventing condensation to increase the interior temperature of the built-in closet by installing the furniture far away from the core and external wall spaces when designing the arrangement of built-in furniture.

Fig. 5(b) shows the interior absolute humidity of the built-in furniture of each subject apartment. For the cumulative frequency values of all the subject apartments, the apartments with the values on the right side of the graph have higher absolute humidity. The apartments with the highest absolute humidity were K, G, A, and D. These are the apartments where condensation problems occur, and the absolute humidity was higher in comparison to the rest of the apartments. The apartments found to have condensation problems from the interview matched the apartments with high absolute humidity. The degree of absolute humidity of the occupying space is thought to have a close relationship with condensation development. It is necessary to consider a system of facilities, such as ventilation and exhaust, to reduce the amount of absolute humidity to a level where condensation and mold cannot develop.

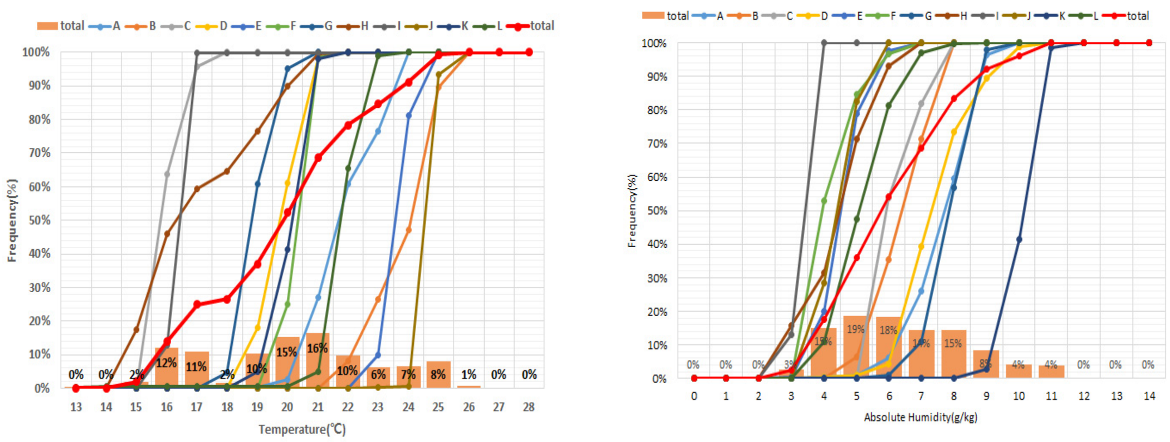


Fig. 5. (a) Temperature and rate of accumulation for each apartment in winter; (b) absolute humidity and rate of accumulation for each apartment in winter.

3.3. Summer

The temperature and relative humidity of the nine target apartments were measured in the summer. The interior temperature of the built-in furniture was a maximum of 30.8 °C, minimum of 23.4 °C, and mean of 28.1 °C, and the relative humidity was a maximum of 83.2%, minimum of 36.0%, and mean of 65.0%. (Table 4)

The interior temperature distribution of the built-in furniture ranged between 23 °C and 31 °C. The temperatures of the balcony, living room, and room with the built-in furniture showed similar distributions, ranging from 22 °C to 30 °C. The temperature distribution during the summer was similar to that of adjacent rooms. In the case of the interior absolute humidity of the built-in furniture, as it is a value that demonstrates the amount of water vapor in the occupying space, and the influence of the humidity on the interior thermal environment of the built-in furniture was studied. The interior absolute humidity of the built-in furniture had a direct effect on the quantity of water vapor in the balcony, living room, and the room with built-in furniture (Fig. 6).

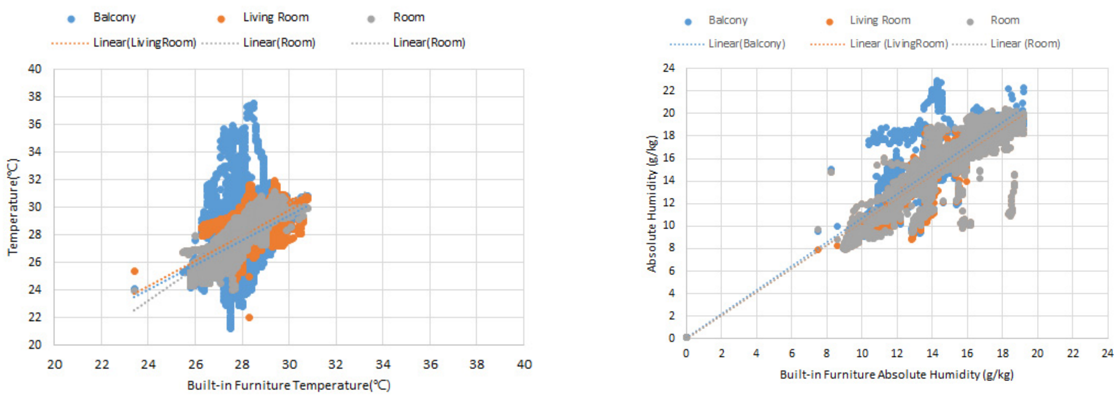


Fig. 6. (a) Correlation between built-in furniture temperature and balcony, living room, and room temperature during summer; (b) correlation between built-in furniture absolute humidity and balcony, living room, and room absolute humidity during summer.

Fig. 7(a) shows the interior DBT of the built-in furniture for each apartment. The total line in Fig. 7(a) is a set of cumulative frequency graph values of all measured apartments, and if an apartment is placed on the right side of the total line, it means that the temperature of the built-in furniture is high. The apartments with a high interior temperature of their built-in furniture were H, G, and I. The apartments with a low interior temperature of their built-in furniture were L, J, C, and E. In contrast to the winter results, the temperature difference between apartments during summer was not big, and the influence of this characteristic on the layout of apartment was low.

Fig. 7(b) shows the interior absolute humidity of the built-in furniture of each apartment. The total line indicates the cumulative frequency values measured from all subject apartments, and the apartments located on the right side of the total line have high absolute humidity, including G, L, and D. These apartments had higher absolute humidity in comparison to the rest of the subject apartments. Apartments G and D, in particular, had condensation problems during winter, and the occupants were continuously exposed to a humid environment, in general. Apartment L is located on the ground floor, which means there is a large possibility of influence from absolute humidity coming up from the ground and absolute humidity of the interior space flowing into the interior of the built-in furniture through the gallery door.

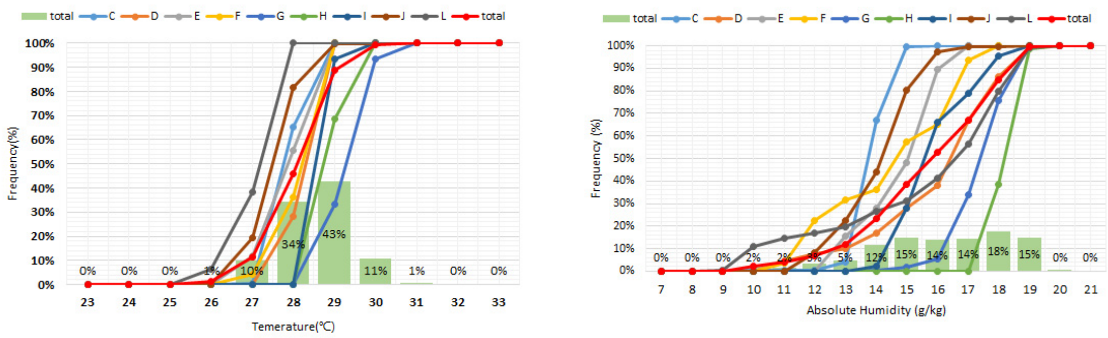


Fig. 7. (a) Temperature and rate of accumulation for each apartment during summer; (b) absolute humidity and rate of accumulation for each apartment during winter.

4. Discussion

As demonstrated in Fig. 1, the areas around the built-in furniture where condensation and mold usually grow up were confirmed to be the air space between the back panels of the built-in furniture and the building structure, as demonstrated by the condensation and mold damage cases in Korean multifamily buildings. It is necessary to consider both the influence of condensation caused by the temperature difference between the interior and exterior due to the drop of surface temperature of a building and the influence of excessive humidity generated in the interior from a lack of ventilation. As shown in Fig. 1(d), it may be more precise to measure the temperature and relative humidity of the air space existing between the back panels of the built-in furniture and the wall of the building structure. However, considering potential damages that may be caused to the back panels of the built-in furniture, which in turn, may alter the structure stability and cause damage to the property of the occupants residing in the subject apartments, the above-mentioned area was not measured. Instead, it was determined that it would be possible to predict the thermal environment of the air space between the back panels of the built-in furniture and the wall of the building structure through the interior thermal environment of the built-in furniture.

The mold growth and the conditions for interior comfort can be represented in a psychometric chart (Fig. 8) [20]. Mold growth is influenced by various factors, including temperature, relative humidity, nutrition, and pH. It is suggested that the best thermal environment for mold is between 90%–95% relative humidity and 20 °C–30 °C. It is important to maintain the thermal environment within a range that does not satisfy the above-mentioned conditions inside the built-in furniture, to prevent mold growth. Condensation inside the built-in furniture occurs when the interior surface temperature of the furniture is lower than the interior dew point temperature of the furniture. Condensation will not occur if the interior temperature of the furniture is higher than the maximum dew point temperature indicated in the psychometric chart. Fig. 8 presents the psychometric chart of the thermal environment observed during summer and winter.

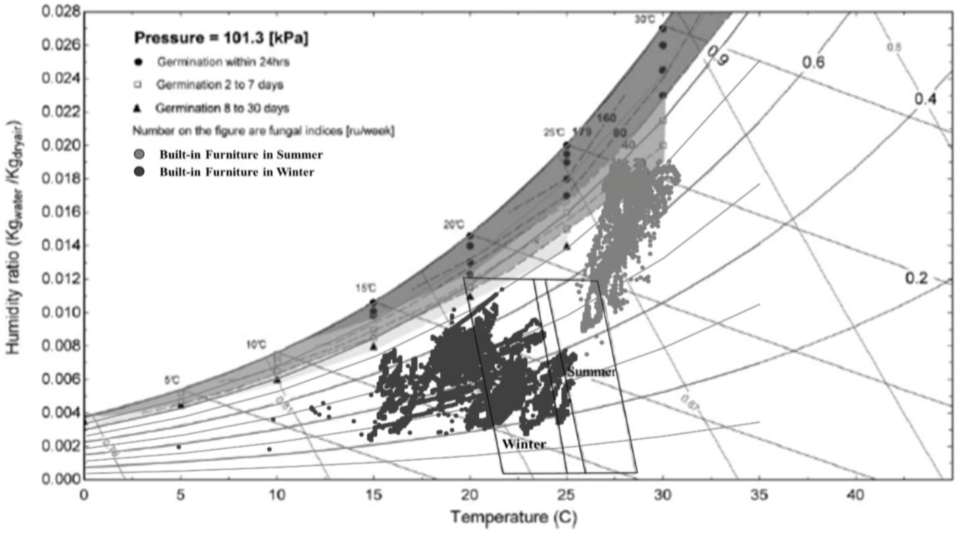


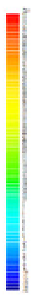
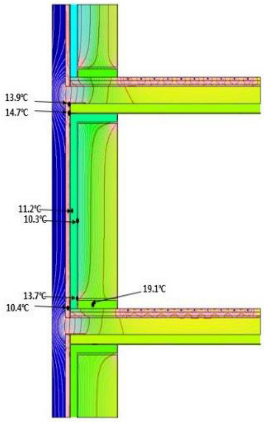
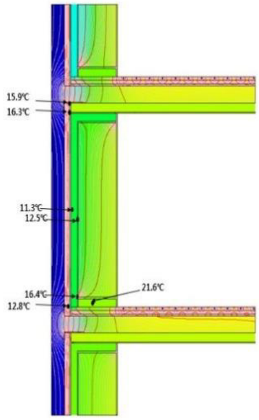
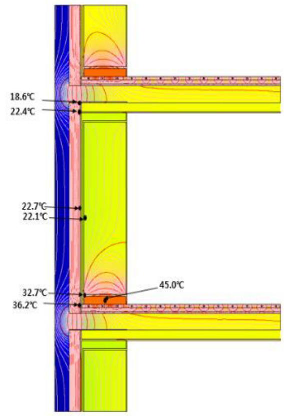
Fig. 8. Psychometric chart of mold index and measured points during summer and winter.

During summer, an absolute humidity over 0.016 kg/kg on the psychometric chart falls into the range of enhancing mold growth. During summer, the interior absolute humidity of built-in furniture was over 0.016 kg/kg more than 50% of the time, as represented in Fig. 6(b). Because the exterior environment is hot and humid, it is hard to reduce the absolute humidity by ventilation. An effort should be made to decrease the amount of absolute humidity in the interior space through dehumidification facilities to maintain the environment without mold growth. Currently, the occupants of multifamily buildings intermittent cool and dehumidify their apartments with chemical desiccants and air-conditioning devices. In winter, a thermal environment that encourages mold growth was not observed. It was confirmed that occupants might be exposed to a thermal environment that has an effect on the development of condensation and mold if they live within a certain part of the most comfortable range of thermal environment during winter. To prevent condensation inside built-in furniture, the surface temperature should be maintained beyond the dew point temperature because it is thought that condensation will not occur if the surface temperature is maintained higher than 16 °C (dew point temperature), which was confirmed in the psychometric chart in Fig. 8. However, the apartments constructed after 2004 showed higher absolute humidity values in the apartment interior. This means that occupants living in multifamily buildings of reinforced insulation and airtightness performance need appropriate ventilation and exhaust. Based on the analysis of the measured data, it will be possible to adjust the thermal environment to inhibit the development of condensation and mold by installing proper facilities for ventilation and exhaust around the built-in furniture and other areas inside the apartment to reduce the absolute humidity.

In Korea, regulations will be modified in June 2016 to reinforce the insulation of the wall area around built-in furniture and to prevent built-in furniture from being installed in the external wall area. An additional suggested modification is to increase the temperature of air space between the back panels of built-in furniture and the building structure by minimizing the distance of the floor heating coil adjacent to the furniture.

A thermal analysis simulation was performed to study the influence of the thermal environment occurring around built-in furniture during winter. The effect was studied between the apartments with matching wall U-values and the new apartments built based on the new building standards. The results show that it is difficult to maintain the surface temperature above 16 °C around built-in furniture. It is thought to be highly effective to follow the new regulations and enhance the insulation performance to heat the apartments (Table 5).

Table 5. Thermal analysis results regarding surface temperature.in winter

	Apartments A,B,D,G,H,J	Apartment K	New apartment by 2016
Temperature Distribution (60°C)  (-15°C)			
U-value of wall (W/m2K)	0.47	0.36	0.21
Minimum Temp. Built-in furniture (°C)	10.3	12.5	22.1
Air Temp. between furniture and wall (°C)	11.2	11.3	22.7

5. Conclusions

The thermal environment around built-in furniture installed in multifamily buildings was measured during summer and winter to provide baseline research for the prevention of condensation and mold growth in the interior of built-in furniture in apartments. The results are as follows:

(1) The vulnerable areas to the condensation and mold problems in built-in furniture were the back panels of the furniture, wall side of the building structure, ceiling, corners adjacent to the floor, and air space around the wall side.

(2) During winter, the interior thermal environment of built-in furniture is influenced by the living environment of the occupants in the room and living room areas. It would be beneficial not to install built-in furniture in areas adjacent to external walls and core space. During winter, condensation may cause more damages, and it will not occur if the interior surface temperature of built-in furniture can be maintained above 16 °C. Thus, measures to increase the interior surface temperature of built-in furniture should be considered.

(3) During summer, the hot and humid exterior thermal environment influences that of the interior of built-in furniture. The amount of interior absolute humidity of built-in furniture was exposed to the range of the thermal environment that encourages mold growth. It is necessary to put extra effort into reducing the amount of interior

absolute humidity of built-in furniture by applying chemical desiccants along with intermittent use of air conditioners and dehumidifiers.

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